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(71) Applicant *(for all designated States except US)*: MCNC [US/US]; 3021 Cornwallis Road, P.O. Box 12889, Research Triangle Park, NC 27709-2889 (US).

(72) Inventors; and
(75) Inventors/Applicants *(for US only)*: DHULER, Vijayakumar, R. [IN/US]; 8301 Trumpetor Way, Raleigh, NC 27613 (US). WALTERS, Mark, David [US/US]; 103 Cricket Ground, Durham, NC 27707 (US). HILL, Edward, A. [US/US]; 312 Forbush Mountain Drive, Chapel Hill, NC 27514 (US). COWEN, Allen, Bruce [US/US]; 206 Phauff Court, Cary, NC 27513 (US).

(74) Agents: EDWARDS, James, C. et al.; Alston & Bird LLP, P.O. Drawer 34009, Charlotte, NC 28234-4009 (US).

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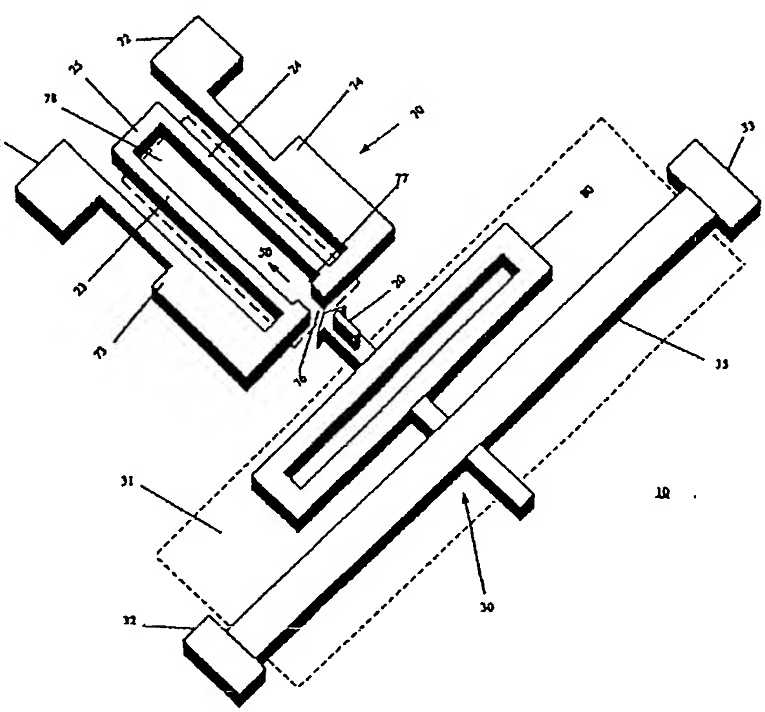
(54) Title: MOVEABLE MICROELECTROMECHANICAL MIRROR STRUCTURES

(57) Abstract

Microelectromechanical structures (MEMS) are provided that are adapted to controllably move mirrors in response to selective thermal actuation. In one embodiment, the MEMS moveable mirror structure includes a thermally actuated microactuator adapted to controllably move along a predetermined path substantially parallel to the first major surface of an underlying microelectronic substrate. A mirror (20) is adapted to move accordingly with the microactuator (30) between a non-actuated and an actuated position. In all positions, the mirror has a mirrored surface disposed out of plane relative to the first major surface of the microelectronic substrate. The microactuator provided herein can include various thermal arched beam actuators (35), thermally actuated composite beam actuators, arrayed actuators, and combinations thereof. The MEMS moveable mirror structure can also include a mechanical latch (70) and/or an electrostatic latch for controllably clamping the mirror in position. A MEMS moveable mirror array is also provided which permits individualized control of each individual MEMS moveable mirror structure within the array.



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MOVEABLE MICROELECTROMECHANICAL MIRROR STRUCTURES

FIELD OF THE INVENTION

The present invention relates to microelectromechanical structures, and more particularly to thermally actuated microelectromechanical mirror structures and associated methods.

BACKGROUND OF THE INVENTION

Microelectromechanical structures (MEMS) and other microengineered devices are presently being developed for a wide variety of applications in view of the size, cost and reliability advantages provided by these devices. Many different varieties of MEMS devices have been created, including microgears, micromotors, and other micromachined devices that are capable of motion or applying force. These MEMS devices can be employed in a variety of applications including hydraulic applications in which MEMS pumps or valves are utilized and optical applications which include MEMS light valves and shutters.

MEMS devices have relied upon various techniques to provide the force necessary to cause the desired motion within these microstructures. Some MEMS devices are driven by electromagnetic fields, while other micromachined structures are activated by piezoelectric or electrostatic forces. Recently, MEMS devices that are actuated by the controlled thermal expansion of an actuator or other MEMS component have been developed. For example, U.S. Patent Application Serial Nos. 08/767,192; 08/936,598, and 08/965,277 which are assigned to MCNC, the assignee of the present invention, describe various types of thermally actuated MEMS devices. The contents of each of these applications are hereby

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incorporated by reference herein. Thermal actuators as described in these applications comprise arched beams formed from silicon or metallic materials that further arch or otherwise deflect when heated, thereby creating motive force. These applications also describe various types of direct and indirect heating mechanisms for heating the beams to cause further arching. While the thermally-actuated MEMS devices of these applications are described in conjunction with a variety of MEMS structures, such as MEMS relays, valves and the like, these applications do not describe thermally-actuated mirror assemblies.

However, MEMS devices including moveable mirror structures have been developed. Commonly, MEMS moveable mirror devices have been used to redirect electromagnetic energy traveling along a path, typically a light or laser beam. For instance, U.S. Patent Application Serial No. 08/719,711, also assigned to MCNC and incorporated by reference herein, describes various types of MEMS devices which can rotate a reflective plate about several axes within a framed structure. While these devices can be used for communications, laser printing, or various other applications, these do not provide laterally moveable mirrors.

Lucas NovaSensor of Fremont, California has also developed a variety of MEMS devices including thermally actuated mirror structures. For example, these mirror structures include a matrix addressable thermally actuated mirror suitable for use in an optical switching array. These mirror structures generally include silicon beams connected to the mirror that conduct electrical current and are deflected by the resulting heat in order to position the mirror. In some of the mirror structures, the mirror is conductive and forms part of the electrical heating circuit. Regardless of the manner in which the structures are actuated, the reflective surfaces of the mirrors are disposed in a plane parallel to the underlying substrate when the device is not actuated and can be moved either in plane or out of plane upon thermal actuation.

electrical current

While some thermally activated MEMS mirror structures have been developed, it would still be advantageous to develop other types of moveable mirror structures that would be suitable for a wider variety of applications. For instance, moveable mirror structures that have mirrors disposed out of plane

relative to both the underlying substrate and the direction of movement provided by the actuator are needed. Further, it would be advantageous to provide a MEMS moveable mirror device that could precisely position a mirror and reliably hold the mirror in position, even after the thermal energy used to position the mirror is removed. The efficiency and performance of MEMS mirror devices in applications involving the precise deflection of multiple narrow beams of electromagnetic radiation could thus be improved. For example, high resolution optical switching arrays could be developed from MEMS mirror devices providing these advantageous attributes.

SUMMARY OF THE INVENTION

The present invention provides several embodiments of a moveable microelectromechanical mirror structure that collectively satisfy the above needs and provide several advantageous features. According to the present invention, the moveable MEMS mirror structure includes a thermal actuator and a mirror having a mirrored surface that is disposed out of plane relative to the thermal actuator and to the underlying microelectronic substrate. The MEMS mirror structure provides precise movement of the mirror using the thermal actuator and permits the mirror to be held in a fixed position, even after the thermal actuator is deactivated. Further, MEMS moveable mirror structures may be disposed in an array and individually controlled to serve a variety of switching applications or the like.

In one embodiment, the MEMS moveable mirror structure includes a microelectronic substrate having a first major surface, a microactuator, and a mirror. The microactuator is preferably formed from a single crystal material and is disposed upon the first major surface of the microelectronic substrate. The microactuator is thermally actuated so as to controllably move along a predetermined path that extends substantially parallel to the first major surface of the microelectronic substrate. The mirror is also preferably formed from the single crystal material and is adapted for movement with said microactuator. In particular, the mirror is arranged to move with the microactuator in response to thermal actuation, thus having a non-actuated position and an actuated position.

The actuated position can vary accordingly as the microactuator moves along the predetermined path in response to thermal actuation. According to the present invention, the mirror has a mirrored surface disposed out of plane relative to the first major surface of the microelectronic substrate whether in the non-actuated or actuated position.

In one embodiment, the microactuator of the MEMS moveable mirror structure comprises a thermal arched beam actuator. This actuator includes at least two anchors affixed to the microelectronic substrate and at least one thermal arched beam disposed between the anchors. Each thermal arched beam is adapted to arch further and controllably move along the predetermined path in response to the selective application of thermal actuation. The microactuator can optionally include a spring adapted to flex during selective thermal actuation. While the thermal arched beam actuator need only have a single arched beam, the microactuator of the MEMS moveable mirror structure can comprise a plurality of thermal arched beams. In one embodiment, for example, the plurality of thermal arched beams are arrayed to expand in response to thermal actuation and collectively move along the predetermined path. In another embodiment, the plurality of thermal arched beams are arrayed to compress in response to thermal actuation and collectively move along the predetermined path. In any embodiment, the thermal arched beam actuator can include an electrically conductive path disposed through or upon at least part of the thermal arched beams in order to direct the current flow and correspondingly control the heating of the thermal arched beams.

In another embodiment, the microactuator of the MEMS moveable mirror structure comprises at least one thermally actuated composite beam actuator. This actuator includes at least one anchor affixed to the microelectronic substrate and a composite beam extending from the anchor and overlying the first major surface thereof. Each composite beam has a proximal end connected to an anchor, and a distal end adapted to bend so as to move the mirror along the predetermined path in response to selective thermal actuation, as before. Each composite beam also comprises at least two layers that respond or expand differently to thermal

actuation. The first and second layers may be formed from materials with different thermal coefficients of expansion, such that the distal end bends toward the layer having the lower thermal coefficient of expansion when thermally actuated. An electrically conductive path encompassing the distal end of the composite beam and having variable electrical resistance is defined by the first and second layers of the composite beam, such that current passing along the conductive path causes thermal actuation of the composite beam. Dual thermally actuated composite beam actuator structures with enhanced linear displacement characteristics are provided, including advantageous interconnecting members, interconnecting structures, and platforms used therewith to carry and correspondingly move the mirror.

One embodiment of the MEMS moveable mirror structure further comprises a mechanical latch affixed to the first major surface of the microelectronic substrate. The mechanical latch is adapted to open in response to thermal actuation so as to receive the microactuator. Further, the mechanical latch is adapted to close when thermal actuation is removed to controllably clamp the microactuator in position once the mirror has moved into the actuated position. Once latched, the microactuator and, therefore, the mirror can be held in place even if the microactuator is no longer actuated. In addition, the mechanical latch is adapted to reopen in response to further thermal actuation to release the microactuator. In another embodiment, an electrostatic latch is provided to clamp the microactuator in position. The electrostatic latch includes an actuator electrode disposed on the microactuator and a substrate electrode disposed on the microelectronic substrate. When a voltage is applied between the electrodes, an electrostatic force is created therebetween to controllably clamp the microactuator in position at any position along the predetermined path of movement.

voltage applied

A further embodiment of the present invention provides a MEMS mirror array including a microelectronic substrate and a plurality of microelectromechanical mirror structures. Each mirror structure comprises a microactuator and mirror as described in the earlier embodiments. One or more of the mirrors within the array can therefore be controllably positioned by selectively

thermally actuating the microactuators corresponding to the respective mirrors. For example, the MEMS mirror array can further include an activation matrix having a row activation path and a column activation path operably connected to each moveable mirror structure within the array. Each mirror can thus be controllably positioned through thermal actuation of the respective microactuator by activating the row and column activation paths corresponding to the mirror. As described above, the MEMS mirror array can include a variety of microactuators as well as a spring and a latch, such as a mechanical latch or an electrostatic latch. The MEMS mirror array can also include a source of electromagnetic radiation directed along at least one path intersecting one or more of the mirrors within the array, such that the electromagnetic radiation is redirected by a mirror.

Consequently, the present invention also provides a method of redirecting electromagnetic radiation directed along at least one path using one or more moveable mirror structures. One embodiment of the method comprises the steps of providing at least one source of electromagnetic radiation directed along at least one path, selectively thermally actuating one or more microactuators to controllably move along the predetermined path, controllably moving the mirrors corresponding to the actuated microactuators so as to intersect at least one path of electromagnetic radiation, and redirecting at least one path of electromagnetic radiation intersected by the mirrors. As described above, the mirrors can be clamped in position using the mechanical or electrostatic latches in order to reduce energy consumption.

A method of fabricating an microelectromechanical mirror structure is also provided by the present invention. One embodiment of the method includes the steps of providing a carrier wafer having a first major surface, bonding a single crystal wafer thereto, selectively etching the single crystal wafer to define a mirror having a mirrored surface disposed out of plane relative to the first major surface of the carrier wafer in both actuated and non-actuated positions, and further selectively etching the single crystal material to define a microactuator integral with the mirror. The microactuator is formed with portions released from the carrier wafer so that thermal actuation of the microactuator along the

predetermined path parallel to the first major surface of the carrier material will correspondingly move the mirror between the non-actuated and actuated positions. Other embodiments further define the fabrication of the mirror, microactuator, and latches as disclosed herewith.

Although the foregoing invention will be described in some detail, it will be obvious that certain changes and modifications may be practiced within the scope of the invention described herein.

BRIEF DESCRIPTION OF THE FIGURES

Figure 1 provides a top perspective view of a moveable MEMS mirror structure and mechanical latch according to one embodiment of the present invention.

Figures 2(a), 2(b) and **2(c)** provide top views of various embodiments of the thermal arched beam actuators, according to the present invention.

Figure 3 provides a top view of a MEMS mirror structure including a thermal arched beam expansion array actuator according to one embodiment of the present invention.

Figure 4 provides a top view of a MEMS mirror structure including a thermal arched beam compression array actuator according to one embodiment of the present invention.

Figures 5(a) and **5(b)** provide respectively a plan view and a cross section view taken along line 5(b)-5(b) in Figure 5(a) of a thermally actuated composite beam actuator according to one embodiment of the present invention.

Figure 6 provides a plan view of a dual thermally actuated composite beam actuator and an interconnecting structure according to one embodiment of the present invention.

Figure 7 provides a plan view of a dual thermally actuated composite beam actuator and an interconnecting structure according to another embodiment of the present invention.

Figure 8 provides a side view of a moveable MEMS mirror structure and an electrostatic latch according to one embodiment of the present invention.

Moveable MEMS Mirror Structure

A moveable microelectromechanical mirror structure according to one embodiment of the present invention is shown by a top perspective view in **Figure 1**. One embodiment of the microelectromechanical mirror structure comprises a microelectronic substrate, a microactuator, and a mirror. The microelectronic substrate **10** has a first major surface and serves as a base underlying the MEMS mirror structure. Preferably, the microelectronic substrate used for the present invention comprises a suitable substrate material, such as silicon. For instance, 110 silicon material is particularly advantageous for forming mirror structures. However, other suitable substrate materials may be used, such as glass. Although the microactuator and mirror structures are also preferably formed from a single crystal material, alternatively these structures may be formed from a metallic material, such as nickel. For instance, U.S. Patent Application Serial No. 08/736,598, incorporated by reference above, describes a nickel electroplating process that may alternatively be used to form these structures upon the substrate.

In any case, the microactuator **30** is disposed on the first major surface of the single crystal material and adapted to move in response to thermal actuation. As such, the microactuator is adapted to controllably move along a predetermined path that extends substantially parallel to the first major surface of the underlying microelectronic substrate in response to thermal actuation. Preferably, a trench **31** is formed in the substrate underlying at least a portion of the microactuator, so as to provide thermal isolation and minimize heating losses to the microelectronic substrate. As will be discussed below, various thermally actuated structures can serve as the microactuator and function to move and position the mirror.

The mirror **20** of the microelectromechanical mirror structure is adapted for movement with the microactuator. In this regard, while the microactuator and the mirror can be coupled or connected in a variety of manners, the microactuator and the mirror are preferably formed integrally, such as from the single crystal material, for example 110 silicon. The mirror has at least one mirrored surface, which may be formed from etching the single crystal material, depositing a reflective material such as a metal, or both, as described below. Etching the single

crystal material along a crystal plane is preferred because an atomically smooth surface may be formed. Regardless of the manner in which the mirrored surface is formed, the mirrored surface is disposed out of plane relative to the first major surface of the microelectronic substrate.

As mentioned above, the mirror is adapted for controlled movement with the microactuator. When the microactuator is not thermally actuated, the mirror is in a non-actuated or rest position. As the microactuator is thermally actuated and is caused to controllably move along the predetermined path, the mirror is correspondingly moved to an actuated position. Those skilled in the art will understand that the mirror can assume an infinite number of actuated positions depending upon the extent of thermal actuation of the microactuator and the corresponding position along the predetermined path to which the microactuator and mirror have moved. In either the non-actuated or actuated positions, however, the mirrored surface of the mirror is disposed out of plane relative to the first major surface of the of the microelectronic substrate.

While microactuators according to the present invention can have many different embodiments, microactuators preferably comprise thermal arched beam (TAB) actuators, such as described by U.S. Patent Application Serial No. 08/767,192, the contents of which have been incorporated by reference herein. In this regard, the microactuator of **Figure 1** is a thermal arched beam actuator. The thermal arched beam actuator comprises at least two anchors, for example anchor **32** and anchor **33**. Each anchor is affixed to the microelectronic substrate to provide support for the thermal arched beam actuator. Further, the thermal arched beam actuator includes at least one arched beam **35** disposed between at least one pair of anchors. Each arched beam extends between a pair of anchors such that the ends of the arched beam are affixed thereto and the arched beam is held in place overlying the microelectronic substrate.

As described below, the anchors and the arched beam are preferably formed of a single crystal material, such as silicon, that expands or contracts in response to changes in temperature. Typically, the arched beam is comprised of a material with a positive coefficient of thermal expansion that expands with

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increases in temperature. However, the arched beam can also be created from material that has a negative coefficient of thermal expansion that contracts as temperature increases. In operation, each beam is adapted to further arch in a predetermined direction **50** in response to selective thermal actuation thereof. As a result of thermal actuation, the mirror **20** that is adapted for movement with the microactuator is moved into an actuated position as the arched beam controllably moves along the predetermined path. Once thermal actuation is removed, the arched beam will move opposite to the predetermined direction **50** so as to return to the initial non-actuated or rest position if the microactuator and/or mirror has not been latched into position as described below. Since the mirror moves with the microactuator, the mirror moves accordingly so as to return to the non-actuated position along with the arched beam once the thermal actuation is removed, if the microactuator and/or the mirror has not been latched into position.

One embodiment of the microelectromechanical mirror structure according to the present invention further includes a mechanical latch **70**, as shown in **Figure 1**. The mechanical latch is disposed overlying and affixed to the first major surface of the microelectronic substrate. Preferably, the mechanical latch is affixed through at least two anchors, for instance, anchor **25** and at least one of anchor **71** and anchor **72** as shown. Further, the mechanical latch is adapted to open in response to thermal actuation so as to receive the microactuator **30** and adapted to close once thermal actuation is removed so as to clamp the microactuator in position. As such, once the microactuator is clamped in position, the mirror **20** will be correspondingly held in place, in an actuated position, even after thermal actuation is removed from the microactuator. In order to release the microactuator and mirror, the mechanical latch is also adapted to reopen in response to further thermal actuation thereof. The microactuator is thereby unclamped and released, allowing the microactuator and mirror to return to the rest position in the absence of further thermal actuation of the microactuator.

In operation, the mechanical latch **70** is thermally actuated in order to clamp and subsequently release the microactuator **30**. The mechanical latch may be designed to be responsive to various types of thermal actuation and to have

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In operation, the mechanical latch **70** is thermally actuated in order to clamp and subsequently release the microactuator **30**. The mechanical latch may be designed to be responsive to various types of thermal actuation and to have

numerous different configurations so long as the mechanical latch can selectively receive and hold the microactuator and the mirror in an actuated position and can controllably release the microactuator and the mirror to return to the rest position. In particular, the selective application of thermal actuation to the mechanical latch must sufficiently open the aperture **76** defined by the mechanical latch to receive the microactuator. In addition, the mechanical latch must close the aperture sufficiently once the mechanical latch is no longer thermally actuated so as to clamp the microactuator in position. Further, the mechanical latch must be adapted to controllably reopen the aperture to release the microactuator and allow subsequent motion thereof.

According to the above described embodiment of the present invention, both the microactuator and the mechanical latch require thermal actuation. Thermal actuation of either device can occur through various direct and indirect thermal arched beam heating techniques. According to the heating techniques described in the above mentioned U.S. Patent Application Serial No. 08/767,192, the microactuator and the mechanical latch can be thermally actuated by various direct and indirect heating mechanisms. As such, the microactuator and/or the mechanical latch can include an external heater for indirectly heating the respective component. Alternatively, current can be passed through at least a portion of the microactuator and/or the mechanical latch in order to directly heat and thermally actuate the respective component. In the embodiment of **Figure 1**, the mechanical latch is thermally actuated by direct heating. In this regard, a controlled electrical current can be directed through mechanical latch **70** to heat and therefore selectively thermally actuate the mechanical latch. In order to open the aperture defined by the mechanical latch, portions of the mechanical latch must therefore be differentially heated. Preferably, this differential heating is accomplished by designing the mechanical latch such that different portions of the latch have different cross sectional areas and therefore have different electrical resistances which, in turn, creates differential heating when current flows through the latch. For example, portions of the mechanical latch that have smaller cross sectional areas will have a higher electrical resistance and will therefore be heated more and

crossbeams are not coated with the conductive material to force the majority of the current to flow from contact pad to contact pad through the arched beams, as described below.

In operation, the TAB compression array actuator is thermally actuated by passing current through the arched beams, such as by creating a voltage differential between the contact pads **105** and **110**. As the current flows along the path of conductive material, heat is generated accordingly along the thermal arched beam. Heat is conducted from the path of conductive material into the remainder of the arched beams, thereby heating the arched beams. As such, each beam arches further, thus contracting or compressing each diamond shaped cell as each pair of beams come closer together in response to thermal actuation. Collectively, the compression or contraction of each pair of beams causes the TAB compression array to move in preselected direction **52,** thereby moving the mirror **20** accordingly. When current is removed, the pair of arched beams within each bowtie shaped cell reassume the non-actuated position unless the microactuator has been latched in place as described above.

The MEMS moveable mirror structure of the present invention can also include other types of thermally actuated microactuators. As before, thermal actuation occurs due to a relative change in temperature that causes some structures to move relative to other structures. For instance, structures such as thermal arched beams can be heated or cooled differently than adjacent structures, such that the arched beams may be thermally actuated. In particular, the MEMS moveable mirror structure can include a thermally actuated composite beam microactuator. As with the aforementioned microactuators, these composite beam actuators are adapted for thermal actuation through direct heating techniques. As before, the thermally actuated composite beam actuator can move along a predetermined path that extends substantially parallel to the first major surface of the microelectronic substrate. Further, the composite beam actuator can be adapted to carry and correspondingly move the mirror and/or be adapted for latching by a mechanical latch or electrostatic latch as required. In addition, a plurality of